REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1997

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
Dynamic Magnetic Compaction for Near Net Shape Forming of Advanced Material Products

5. FUNDING NUMBERS
DAAH04-94-C-0073

6. AUTHOR(S)
Bhanu Chelluri

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
IAP Research, Inc.
Dayton, OH 45429

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park,, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 33945.1-MS-SB2

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

During the SBIR Phase II study, we have applied Dynamic Magnetic Compaction (DMC) technology for compacting the steel powders to high densities of 7.6 gms/cc. The conventional die pressing will yield densities of ~ 7.2 gms/cc in steel powders. Auto market, requires new methods to produce high density (> 7.5 gms/cc) parts in a cost effective manner. Currently, the wrought or forged material is machined into a given shape and thus the part cost is high. We have shown the potential of the DMC technology to manufacture high density net shape steel parts such as the cylinders, rings, and parts with internal features . During the Phase II project we have initiated the DMC process study through the compaction and modelling.

Towards the end of SBIR Phase II project, IAP Research, Inc., was awarded an Applied Technology Program (ATP) award of $8.7M for three years with General Motors and Zenith Sintered Products, Inc. (auto P/M part producer) as joint venture partners to continue the study on DMC process and bring the technology to the preproduction stage.

14. SUBJECT TERMS

15. NUMBER IF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Dynamic Magnetic Compaction for Near Net Shape Forming of Advanced Material Products

Final Report
Contract No. DAAH04-94-C-0073

Prepared for:

Army Research Office
P.O. Box 2211
Research Triangle Park, NC 27709-2211

Prepared by:

IAP Research, Inc.
2763 Culver Ave.
Dayton, OH 45429-3723

EXECUTIVE SUMMARY

Under the current SBIR Phase II program, we have made technically sound progress, selected the right product focus and brought the technology into a stage ready for Phase III commercialization.

Commercial Highlights:

We have established contacts with General Motors Powertrain (GM) and Delphi Advanced Technologies as OEM's and Zenith Sintered Products as P/M parts maker for the auto industry during the Phase II of this project. The above companies were interested in Dynamic Magnetic Compaction (DMC) process to produce high density parts at a low cost. They started preliminary testing using their powders during Phase II and participated in the technical meetings.

They understood the potential of the process and development effort required to mature DMC technology to the production stage. As a result, towards the end of Phase II, IAP Research, Inc. submitted a proposal to the Department of Commerce under the Advanced Technology Program (ATP) with GM and Zenith as joint venture partners to mature DMC technology. The proposal won and resulted in award of $8.7 million. The ATP program began in September of 1995. The ATP program is progressing well and is on schedule. Our goal under the ATP program is to bring the technology to pre production stage and mitigate the technical risks.

Technical Highlights:

We selected two critical materials to investigate during the Phase II project. These were 4401 steel alloys and plastic coated iron powders for making high density parts. We identified the key DMC process parameters for obtaining high densities such as compaction pressure and temperature. Secondary process parameters such as the powder filling methods to improve the packing characteristics and shape uniformity of the compacted part were also studied. We also made equipment progress by studying the coil designs and improvements to increase their life. We started paper studies on the energy requirements of the power supply and the capital cost of the DMC equipment.

TECHNICAL RESULTS

PROCESS DEVELOPMENT RESULTS

Process Results on 4401 Powders:

Several test cylinders 1.25" long and 0.5" in diameter were fabricated to study the compressibility curves of 4401 powders under the DMC process. The compressibility curves obtained are shown in Figure 1. The feasibility of obtaining a high density of 7.6 g/cc in alloy 4401 steel powder and 7.4-6.5 g/cc in plastic coated steel powders was demonstrated.

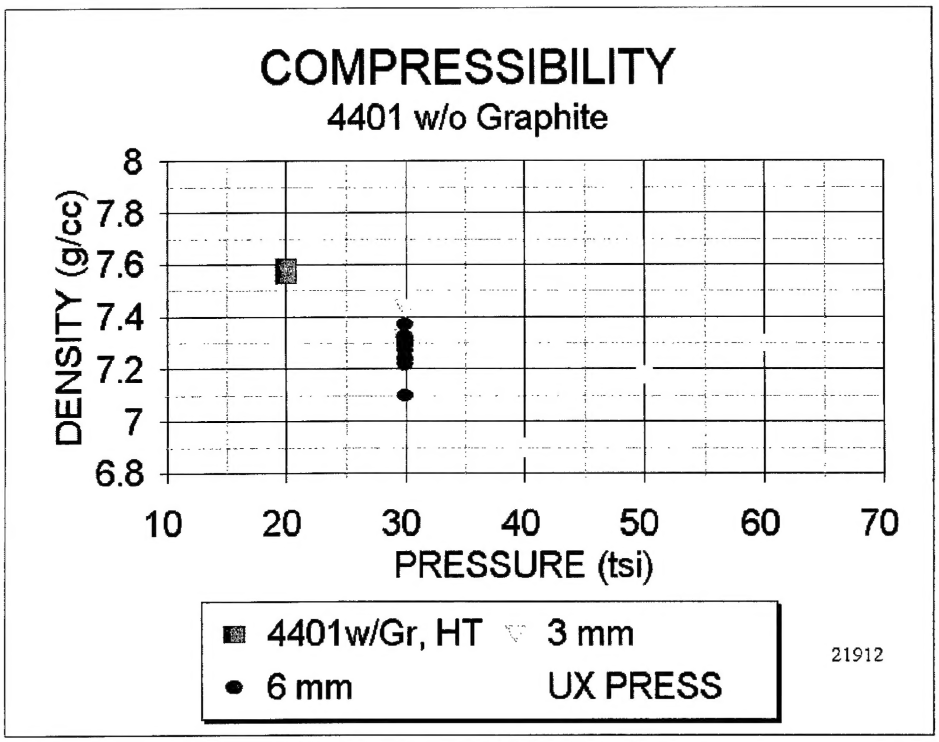

Figure 1. Compressibility curve of 4401 powders.

At a pressure of 20 tsi and temperature of 750°C, the densities of 4401 powder with graphite were 7.6 g/cc. At room temperature and a pressure of 30 tsi, the densities were as high at 7.35-7.40 g/cc. We believe that by increasing the pressure to about 40 tsi and lowering temperatures to 200-300°C, the desired density of 7.6 g/cc may also be obtained. Such a pressure and temperature range is feasible in a production -type environment and we will be conducting compaction tests in this range. The compressibility of the same powders carried out under conventional uniaxial pressing

was found to be lower than DMC, even at pressures as high as 60 tsi. The enhanced compressibility could arise from dynamic effects of the DMC pulse process.

In addition to the compressibility data, the uniformity in density and green strength were measured, and micro structural characterizations were made. The density measurements were made using the liquid displacement method and axial variations in densities were evaluated by sectioning the specimens in axial and radial directions. Figures 2 and 3 show the density variations in the axial direction for 0.5" and machined cores of 0.4" diameter respectively. The green strength and micro structural characterizations were to evaluate the degree of bonding at the particle boundaries as a result of the DMC process.

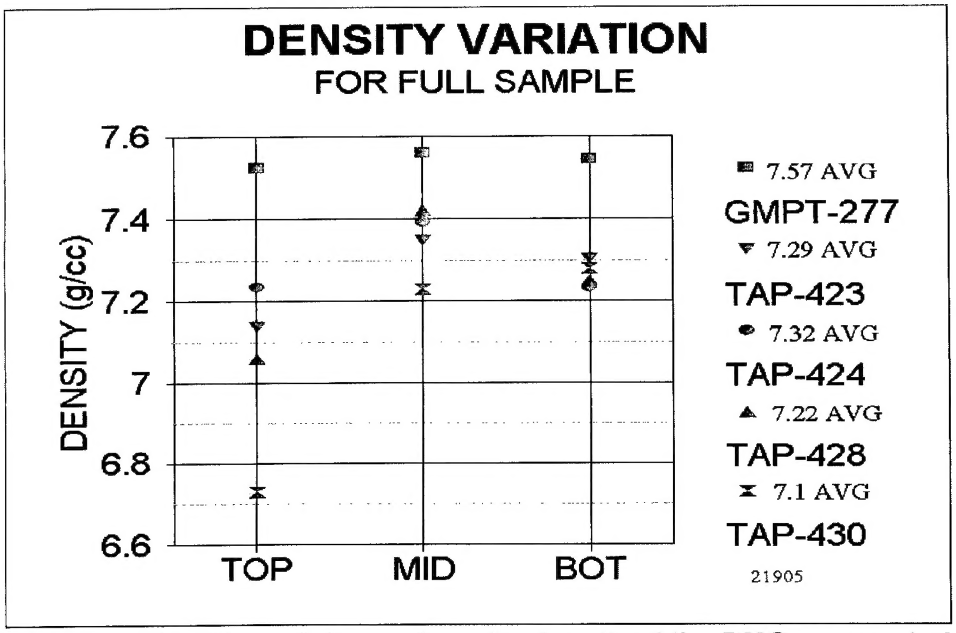

Figure 2. Density variations along the length of the DMC-compacted sample. The sample is 1.2" long and 0.5" in diameter. The density variations are measured by sectioning the sample into three pieces with end pieces 0.25" long and a middle piece 0.75" long.

Figure 2 shows the variation in density for five different samples. In general, all samples exhibited a variation in density. The top segment was normally less dense than the middle and lower part of the sample. The reasons for this variation are unclear and details need to be investigated.

Figure 3 shows the variation for four different samples. These samples had the outer surface machined off, so that only 0.4" of the original 0.5" diameter remained. The cores appear to be more dense than the surface of the samples. We are exploring different possibilities for why this occurs so that in the real production process such variations can be eliminated. We will be conducting a detailed study of these effects in our next program.

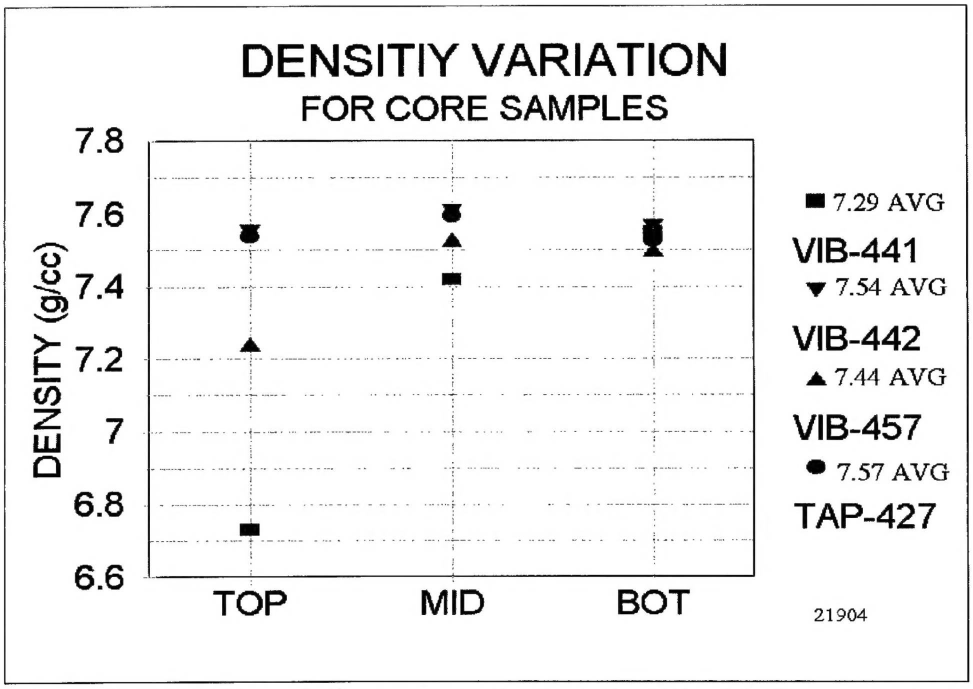

Figure 3. Density variations along the length of the DMC compacted sample after machining to the core diameter of 0.4" The axial density variations are measured by sectioning the sample into three pieces with end pieces of 0.25" and middle piece of 0.75" long.

Different powder fill methods such as tap and vibration were systematically investigated. The problems of powder settling, segregation, and non-uniformity in the compacted specimen were due to pre-compaction handling and can be minimized by using appropriate powder filling parameters and methods. Filling via a tap method with a tap amplitude of <3 mm yielded the best densification and final sample shape. Figure 4 shows the dramatic effect on final shape of the sample depending on the initial powder filling method. The result indicates the fill method will be an important parameter in optimizing the density and uniformity of compacted parts.

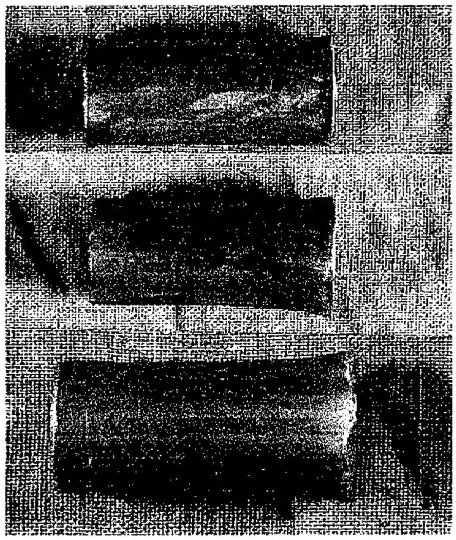

Figure 4. The effect of fill method on the final shape of compacted sample.

Results on Plastic Coated Steel Powders:

We have investigated three types of plastic coatings (A, B, and C), and the compressibility of each of these powders using the DMC process. Powder B has shown the highest compressibility. Compressibility curves of powders A, B, and C are within the available data and are shown in Figures 5, 6, and 7 respectively. Each graph shows the densities achieved at pressures ranging from 15 to 35 tsi and temperatures of 22 °C, 150°C, and 260°C. Reaching our density goal of 7.5-7.6 g/cm^3 at these pressures and temperatures was exciting, because they should be readily attainable in a production-scale system. With pressures of 35 tsi and a temperature of 150°C, a density of 7.6 g/cc was achieved in powder B.

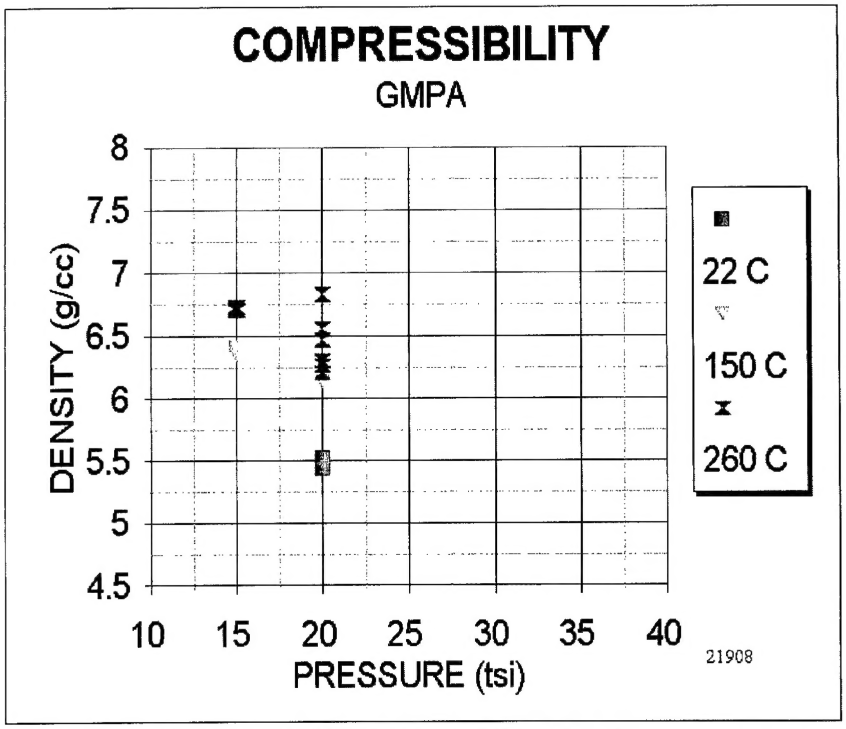

Figure 5. Compressibility curve of Powder A.

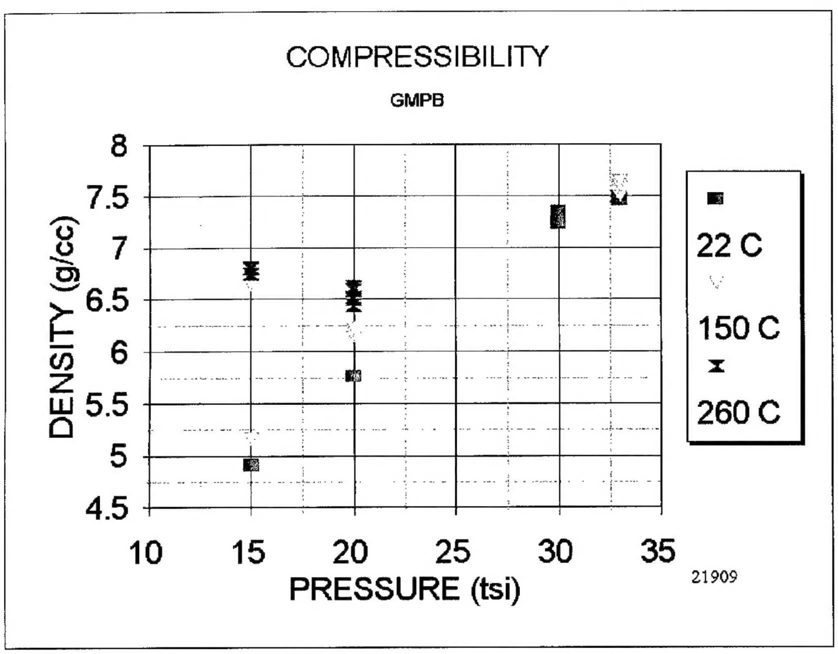

Figure 6. Compressibility curve of Powder B.

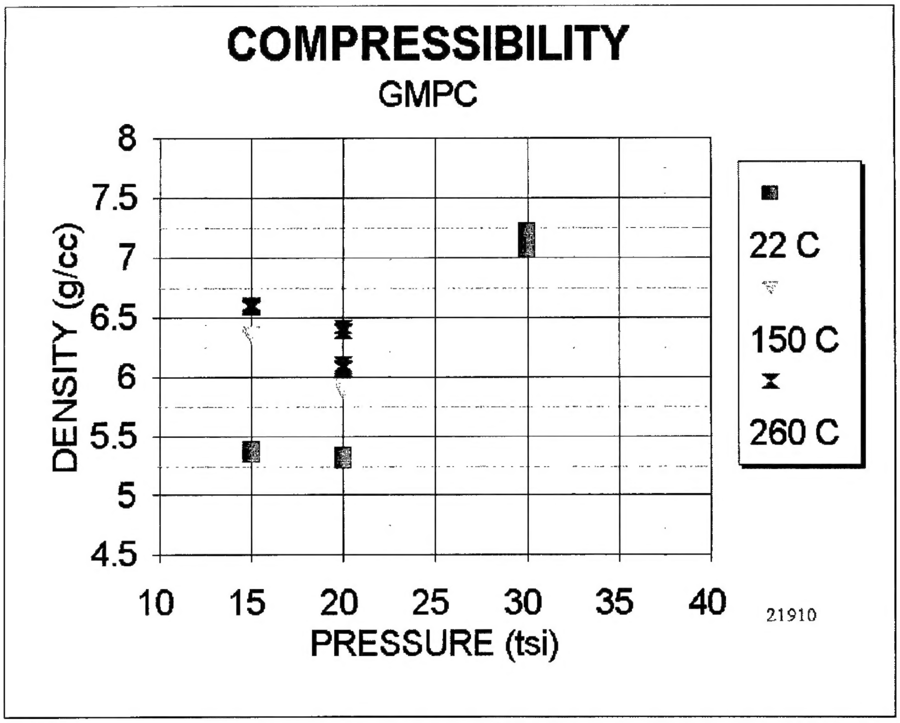

Figure 7. Compressibility curve of Powder C.

EQUIPMENT DEVELOPMENT RESULTS

Our goal in DMC equipment development is to build robust, long life machinery that will deliver repeatable intense magnetic pulses. Our major technical challenges are in improving the life, pressure capability, and safety of the magnetic coils and power supply. The hard tooling (i.e., dies) also presents a key hurdle, although we believe that the vast conventional P/M tooling experience base will provide a considerable foundation for DMC tooling. Several support equipment technologies must also be developed, including armature fabrication and "recycling," part extraction, and powder filling/pre-post compaction handling. Our primary equipment focus was on developing more robust magnetic coils, and upgrading power supply performance for DMC specimen processing.

Magnetic Coils:

Pulsed magnetic fields have seen limited industrial use for forming metals for more than 25 years. In these applications, peak magnetic field intensities of about 10 to 15 Tesla are typical. In DMC, we anticipate needing magnetic fields in the 30 to 40 Tesla regime, which is equivalent to a magnetic "pressure" of 350 to 650 Mpa, or about 4 to 8 times the magnetic pressures used for metal forming. One key challenge is to develop

the coil technology needed for long life, robust coils that can reliably operate at these high pressure levels.

During the past 3 to 4 years that we have been working on the DMC process, we have tried alternative coil construction designs/architectures. Until late in the summer of 1995, we made coils by machining (using electrodischarge machines, (EDM)) narrow helical grooves into solid conductive round bar stock. With a suitably strong bar stock material, very high strength coils can be made. We have used these solid helix style coils up to field levels as high as about 50 Tesla. Unfortunately, this type of coil places the turn-to-turn electrical insulation under very high mechanical pressure, resulting in insulation failure after only a few tens of pulses. A photo showing a solid helix coil with failed insulation is provided in Figure 8. The other negative feature of this style coil construction is that only a limited number of companies in the U.S. possess the specialized EDM equipment needed to cut the helical grooves.

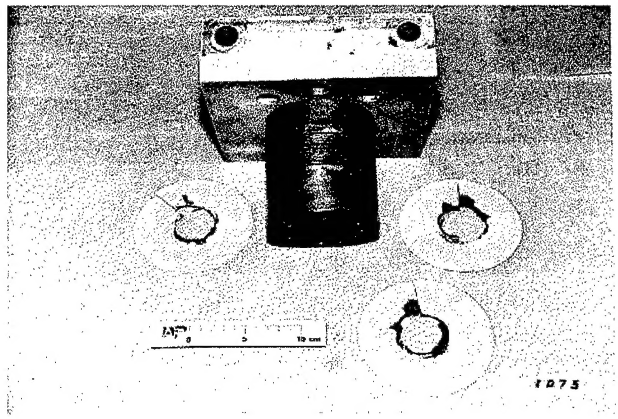

Figure 8. Turn-to-turn insulation durability is a serious drawback for solid helix coil contruction.

Since the summer of 1995, we have been developing a “flux shaper” coil construction to overcome the inadequacies of helix coil designs. One key advantage of this architecture is that the windings operate at a lower magnetic flux intensity than that at the coil bore. The shorter axial length at the bore compared to the outer surface of the shaper, effectively causes a flux compression, allowing the windings to operate at magnetic pressures suitable for insulating materials, while creating high magnetic pressures at the bore. Since implementing the flux shaper designs, we have not had a single winding insulation failure, with accumulated pulses into the hundreds, so far.

Several shapers have been fabricated and used to compact P/M specimens during this project. Most of these shapers were made of aluminum alloy 7075-T6 material. Two of the shapers that were operated at 30 Tesla for about 125 pulses have developed radial cracks, initiating at the bore. The cracks initiate at the corners on each end of the bore after tens of pulses, grow axially until meeting at bore mid length with more pulsing, then grow radially outward with continued pulsing.
We need to perform a thorough analysis of the magnetic loading and stress state imposed on the shaper during pulsing. We will use magnetic finite element analysis (FEA) software to predict the applied magnetic loads in the next program. We input

these loads in a mechanical model of the shaper in our mechanical FEA software to predict the shaper stress state. We have begun to analyze various geometrical alterations to the shaper to attempt to find designs which mitigate the corner stresses. This part of the study will also be continued into the ATP program.

We have fabricated a shaper from Be-Cu alloy material. This material has about twice the mechanical strength of the aluminum alloy, and so far has shown no signs of cracking. The long term fatigue life of the shaper however, will probably require further extensive development effort.

Power Supply:

Our pulsed power supply activity during this reporting period has been focused on implementing a flexible, modular, semi automatic system for powering P/M processing coils. These power supplies will be used to compact P/M specimens throughout the process development phase. Although these power supplies are not appropriate for an industrialized DMC process, we will use them as a test bed to develop the needed power supply componentry. The main areas in power supplies requiring development are switching, controls, and diagnostics.

We have used pulsed power supplies for many years to power electromagnetic railguns being developed for military defense and other purposes. During this project we have converted two existing units of this railgun power supply for powering DMC development.

The power supply conversions required design changes to several components/subsystems, and power connections at the coil. Each of the two power supplies consists of eight individual capacitor-switch-bus work subsystems. On each power supply, the eight capacitors together can store up to 187 kJ of energy and deliver a pulse of current up to 800 kA. One of the two eight capacitor modules has been used to compact the 19 mm diameter specimens.

In the next program, we will begin development work on high pulse power switching for the future industrial DMC power supply.

Conclusion:

The DMC technology initiated under Phase I and II of SBIR project is being continued with the support from ATP funds from the Department of Commerce.
We have industrial customers (GM and Zenith) actively participating in the project with specific product focus. We are currently studying/resolving the process, equipment, and cost issues to bring the technology to a production stage at a fast pace.